BEHAVIOR OF SPINNING SPACE VEHICLES WITH ONBOARD LIQUIDS*

Carl Hubert
Hubert Astronautics, Inc.

ABSTRACT

Although the fundamental principles of spin stabilization are well established, uncertainty regarding the potential for rapid nutation growth caused by onboard liquids is a continuing issue. This is a concern because spinning solid upper stages are likely to be used for at least another decade and because spin stabilization remains appropriate for all or part of some types of scientific and microsatellite missions. Since purely analytical means of predicting the influence of onboard liquids have generally failed, the focus of this study was on identifying, collecting, analyzing, and interpreting available flight and test data for a wide range of spinning vehicles with onboard liquid propellants. The data was normalized and correlated in a form that can be applied to current and future space vehicles and that can serve as a truth model for developing and testing analytical techniques. For some tank configurations it was possible to identify conditions that can lead to resonance between nutational motion and liquid modes and to identify the general characteristics of the liquid motion that causes the problem. Attention was also given to methods for mitigating the effect of undesired liquid behavior.

INTRODUCTION

Although the majority of space vehicles are now three-axis stabilized, spin-stabilization continues to have its applications. Spinning solid upper stages are likely to be used for another decade and spin stabilization remains appropriate for all or part of some types of scientific and microsatellite missions. Although the fundamental principles of spin stabilization are well established, uncertainty regarding the potential for rapid nutation growth caused by onboard liquids is a continuing concern. This concern is prompted by the fact that spacecraft designers regularly equip vehicles with propellant tanks or propellant management devices that have little or no heritage on spinners, and from the fact that tanks with spinning heritage are being applied to configurations that are outside the parameter space of previous experience. Lack of experience with new configurations is an issue because there are no reliable purely analytical methods for predicting nutation growth rates. As of this writing, the only reliable predictive methods are those based on flight or test data for the actual tank configuration that is being analyzed.

One particular concern is the increasing use on spinning vehicles of tanks with cylindrical sections. Such tanks have been shown to be susceptible to strong liquid/nutation resonances. In recent years several missions that used tanks with cylindrical sections required last-minute hardware or operational changes to deal with rapid nutation divergences that were identified late in the program. In some instances major schedule slips were barely averted, and in at least one case it was determined that the use of a spinning upper stage was not a viable option because the effect of the onboard liquid propellant was too severe. Diaphragm and bladder tanks have also seen increased application on vehicles that spin during all or part of their missions. Although the data set for diaphragm and bladder tanks is still relatively sparse, recent test and flight performance has indicated that these tanks can also cause nutation problems.

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Historically, the "slosh" issue has been addressed by each space vehicle project individually, if it has been addressed at all. Due to budgetary and programmatic constraints, individual projects are unable to address the problem globally. Hence, there has been little effort to collect available test and flight data or to use that data to assemble a coherent picture of the effects of onboard liquids and how to deal with them. Furthermore, because most tests focus on unique spacecraft designs, results are almost always reported as predicted nutation time constants for a specific mission rather than in a normalized form that can be applied to a range of vehicle configurations. Thus, each project must to some extent "reinvent the wheel" regarding the effect of onboard liquids. This can be both costly and risky. As a step toward correcting the situation, the NASA Kennedy Space Center funded a study to identify and collect available flight and test data for spinning vehicles with onboard liquid propellants. This data was analyzed, normalized, and correlated. In most cases, the normalization involved a dimensionless nutation time constant that can be used to predict performance of other vehicles with the same type of tank. For some configurations it was also possible to identify conditions that can lead to resonance between nutational motion and liquid modes. The results of that study are published in Reference 1 and summarized in this paper.

TERMINOLOGY

Terminology relating to nutation dynamics and the onboard liquid problem tends to vary from organization to organization. To avoid ambiguity, the following definitions are given for terms as they are used in this paper.

Inertially symmetry: A vehicle is considered to be inertially symmetric if the principal axes perpendicular to the spin axis have identical moments of inertia. An inertially symmetric vehicle is dynamically equivalent to a homogeneous cylinder.

Inertia ratio: The ratio of a vehicle's moment of inertia about it's nominal spin axis (a principal axis) to a principal moment of inertia about an axis perpendicular to the spin axis. By this definition, an inertially asymmetric vehicle has two different inertia ratios.

Effective inertia ratio: The inertia ratio of an inertially symmetric rigid body that has the same nutation frequency as the real vehicle when both are spinning at the same rate. The effective inertia ratio is based on calculated moments of inertia and assumes any onboard liquids to be frozen in their nominal locations.

Apparent inertia ratio: The inertia ratio of an inertially symmetric rigid body that has the same nutation frequency as a vehicle with mobile onboard liquid when both are spinning at the same rate.

Fill fraction: The fraction of a tank's total volume that is occupied by liquid. Note that by this definition a fill fraction of 1.0 may exceed the tank's usable capacity.

GENERAL CHARACTERISTICS OF LIQUID MOTION IN PROPELLANT TANKS

Although motion within propellant tanks is often referred to by the generic term "sloshing", there are actually three completely different types of liquid behavior that affect nutation dynamics and rotational stability: bulk motion, surface wave sloshing, and subsurface inertial waves. These behaviors are illustrated in Figure 1.

Free Surface Sloshing

As shown in Figure 1, sloshing is characterized by an undulation of the free surface. As such, it can only occur in partially-filled tanks. Small-amplitude sloshing typically involves a cyclic surface oscillation at a well-defined frequency. Except when the tank has a low fill fraction, small-amplitude sloshing causes relatively little liquid movement at the bottom of the tank. Large-amplitude sloshing is more complex, and can involve splashing and breaking waves. This more vigorous behavior usually occurs in response to sharp transients, such as solid motor ignition and burnout.

In most tanks that are offset from the vehicle's spin axis, the lowest sloshing frequency is well above the nutation frequency. This usually precludes a strong interaction between free-surface sloshing and nutational motion. Under

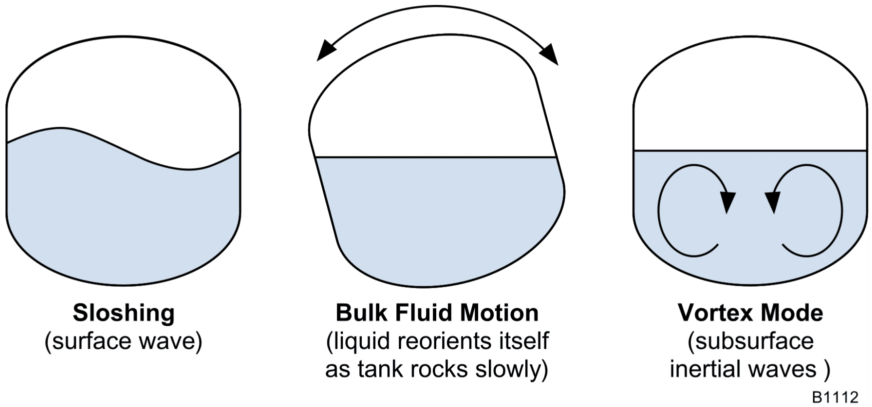

Figure 1. Three types of liquid motion

such conditions, surface waves are small and have only a second-order effect on energy dissipation. However, if the spin axis passes through a tank the dynamics are quite different and vigorous large-amplitude surface waves can occur. This behavior, which is shown conceptually in Figure 2, is variously known as a "swirling", "rotary slosh", or "nutation synchronous" motion. As the figure shows, the motion is characterized by a unidirectional wave that swirls around the tank at the nutation frequency. The further a partially-filled centerline tank is from the vehicle's center of mass, the easier it is to excite this behavior and the more vigorous the motion will be once it starts. On a minor-axis spinner the wave is retrograde. In other words, when viewed from a coordinate frame fixed on the vehicle, the wave moves around the tank in a direction opposite to the spin. On a major-axis spinner the wave is prograde, meaning that the flow is in the same direction as the vehicle's spin.

Nutation synchronous motion typically has two phases. The first is a mode transition during which liquid pools toward one side of the tank and – after a period of increasingly large oscillations – begins swirling around the tank at the nutation frequency. This transition can be extremely rapid, with the mode being fully established within 2 or 3 nutation cycles. The immediate effect of this mode transition is that it establishes a rotating dynamic imbalance, which is visible as an extremely rapid jump in the nutation amplitude. Harrison [2] refers to this type of behavior as a "momentum transfer mode" because it involves an exchange of angular momentum between the liquid and the rest of the vehicle with no significant change in kinetic energy. Once nutation synchronous motion is established, unidirectional flow rapidly dissipates kinetic energy. Although nutation amplitude does not change as rapidly during this second phase as it does during the mode transition, it can still be quite rapid. This can be a serious problem if the vehicle is a minor-axis spinner.

Nutation synchronous motion in on-axis tanks is a complex phenomenon that has seen little mention in the published literature. There has, however, been substantial mathematical and experimental treatment of a similar behavior in circular heat pipes and viscous ring nutation dampers. The problem was discussed by O'Hern et al. [3], who analyzed the 1969 ATS-V mission failure that dramatically demonstrated how small quantities of liquid can severely affect the stability of a spinning vehicle. ATS-V experienced an uncontrollable 11 second divergent nutation time constant after upper stage burnout. This caused the vehicle to enter flat spin and the mission was lost. The loss was ultimately attributed to energy dissipation by liquid ammonia in sixteen circumferential heat pipes. Of the vehicle's 452 kg., only 1.2 kg were liquid. Nutation synchronous flow in partially-filled viscous-ring nutation dampers has been addressed by Cartwright et al. [4], Alfriend [5], Mingori and Harrison [6], Hubert [7], Hubert and Swanson [8], and others.

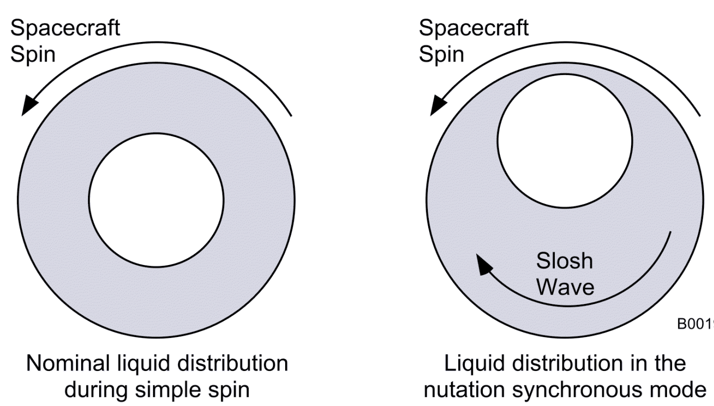

Figure 2. Liquid behavior during nutation synchronous motion on a minor-axis spinner (view is down the vehicle spin axis)

Bulk Fluid Motion

Bulk fluid motion is characterized by liquid reorienting itself within a tank in response to changes in the tank's alignment relative to the acceleration field and/or inertial space. For example, when a half-filled coffee cup is slowly tilted, the free surface remains horizontal as the liquid repositions itself to minimize its gravitational potential energy. If the cup is slowly rocked back and fourth, the liquid continually reorients itself relative to the sides of the cup with little or no rippling of the free surface. This behavior is shown in the middle illustration in Figure 1.

On a spinning vehicle bulk fluid motion is similar to that of the coffee cup example except that the liquid is held in place by centrifugal force instead of gravity and the free surface is a cylindrical segment instead of flat. Nutation produces a cyclic bulk motion that dissipates kinetic energy due to viscous drag as the liquid flows past the tank walls and propellant management devices (PMD's). Unlike free-surface sloshing, bulk motion affects the entire body of the liquid. This means that it can produce much more flow past a PMD than surface wave motion. Under non-resonant conditions bulk motion can dissipate far more energy than free-surface sloshing. On vehicles with off-axis spherical tanks, bulk motion past PMD's is usually the principal energy dissipation mechanism.

It should be noted that bulk motion can exist without a free surface. In other words, it can occur in a 100% full tank. Cyclic rotation during nutation causes the tank walls and PMD to move relative to the contained liquid even if the tank has no ullage volume. For some configurations, energy dissipation is greatest when the tank is 100% full.

Inertial Waves (Vortex Modes)

Inertial waves involve subsurface circulation with very little free surface motion. Because the free surface is not directly involved, these waves can exist in a 100% full tank. Inertial waves are driven by cyclic pressure waves from nutation-induced angular motions of the tank wall coupled with Coriolis forces. The involvement of the Coriolis effect means that these waves cannot be replicated in non-spinning tank tests. It also means that analytical modeling of inertial waves is much more difficult than the modeling of liquid motion on a non-rotating vehicle. In particular, the nature of the motion is such that it cannot be emulated by the equivalent pendulum models that are often used to assess liquid/vehicle interactions. This limitation on pendulum models is serious because inertial waves are often the principal energy dissipation mechanism in non-spherical tanks.

Like surface waves, inertial waves have distinct natural frequencies that are a function of tank shape and fill level. However, unlike surface waves in most off-axis tanks, inertial waves can have natural frequencies that are below the spin rate. This means that inertial waves can resonate with nutational motion to produce rapid energy dissipation. These resonances are often very sharp, which means that near a resonance relatively small changes in vehicle inertia ratio or tank fill fraction can produce dramatic changes in nutation growth rates. Although inertial wave modes can theoretically exist in tanks of any shape, they can only be excited in non-spherical tanks. As shown in Figure 3, cyclic angular motion causes a spherical tank's wall to move in a direction parallel to the wall, and this motion couples with the contained liquid only weakly through viscous shear forces. With a non-spherical tank, however, cyclic angular motion gives the tank wall a component of linear displacement that is perpendicular to the wall. This perpendicular displacement can produce a vigorous motion within the contained liquid.

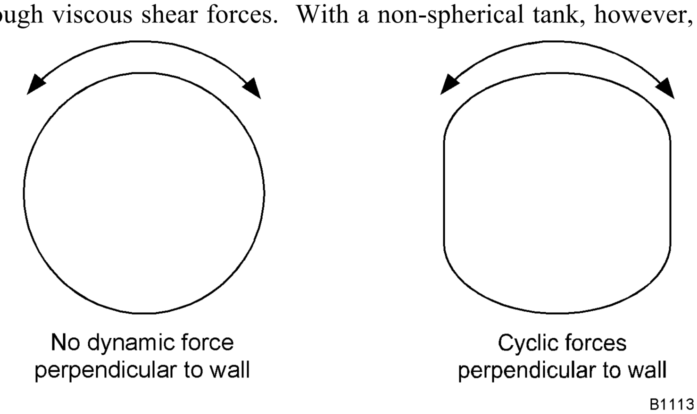

Figure 3. Cyclic rotation produces force components perpendicular to the tank wall in non-spherical tanks, but not in spherical tanks

APPLYING FLIGHT AND TEST DATA TO OTHER VEHICLE CONFIGURATIONS

Passive energy dissipation causes the nutation amplitude to change exponentially if the dominant dissipation mechanism is viscous damping. Viscous damping is also known as linear damping because the associated forces and torques are proportional to the relative rate between two components (e.g., between a liquid propellant and the tank wall). On a nutating vehicle with linear damping the mean energy dissipation rate is proportional to the square of the amplitude of the transverse angular rate (the cyclic angular rate perpendicular to the nominal spin axis). This, in turn, means that the energy dissipation rate is proportional to the nutation angle squared. Exponential nutation growth or decay is described mathematically by the following equation.

$$\theta = \theta_0 e^{t/\tau} \tag{1}$$

Here, θ_0 is the initial nutation angle, t is time, and τ is the nutation time constant. The last parameter is the time required for the amplitude to change by a factor of 2.718. Nutation growth is characterized by a positive time constant and decay by a negative time constant. Nutation time constants can readily be determined from flight or test data. However, to apply nutation data from one vehicle configuration to a different vehicle it is necessary to apply scaling laws such as those described by Harrison [2]. Examination of the system dynamics shows that the nutation time constant is a function of the following parameters:

- N ....number of tanks
- r ....tank radius (interior measurement)
- d ....radial offset of the tank center (measured from the vehicle spin axis)
- h ....axial offset of the tank center (measured from the vehicle cm)
- FF ....liquid fill fraction (fraction of the tank volume occupied by liquid)
- ρ ....liquid density
- R_e.........Reynolds number
- I_S..........vehicle spin-axis moment of inertia
- σ_{eff} ....vehicle effective inertia ratio
- Ω ....vehicle spin rate

Tests by McIntyre [9], Marcè, et. al. [10], and others have shown that in most cases the nutation time constant is relatively insensitive to R_e.* Nutation behavior has also been shown to be relatively insensitive to h and d when the spin axis does not pass through the tank, or when the fill fraction is close to 1.0. On the other hand, flight and test performances have repeatedly shown strong nonlinear sensitivities to fill fraction, inertia ratio, tank shape, and the configuration of internal hardware such as diaphragms, baffles, and propellant management devices.

Based on observations from dimensional analysis, Neer and Salvatore [11] introduced a time constant scaling concept, which they referred to as a "time constant group." Their method worked well and was subsequently used by Agrawal [12], McIntyre [9], and others. Because of this past success, a variant of the Neer-Salvatore scaling approach was used in this study to compare the performance of different tank configurations. This variant, referred to here as the *dimensionless time constant*, is defined by the following equation:

$$T_D = N\left(\frac{\rho r^5}{I_S}\right)\Omega\tau \tag{2}$$

Note that the term ρr^5 in Equation 2 is proportional to the self-inertia of the liquid within a tank. Known values of T_D can be used to determine the time constant for another vehicle with the same type of tank by applying the inverse of Equation 2:

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* "Relatively insensitive" means that the parameter has a second or third order effect, not that it has no effect at all. Time constant calculations based on Equations 2 and 3 should thus be considered approximate rather than exact.

$$\tau = \left(\frac{I_S}{N\rho r^5 \omega}\right) T_D \tag{3}$$

It is extremely important to recognize that Equations 2 and 3 do not include parameters for fill fraction or vehicle inertia ratio. These equations also lack terms that relate to the tank shape or internal hardware. This means that T_D must be determined separately for each tank shape and for each combination of fill fraction and effective inertia ratio. Test and flight experience has repeatedly shown that it is not valid to apply Equation 3 to combinations of FF and σ_{eff} that differ by more than a few percent from those previously tested or flown.

Sensitivity to fill fraction is apparent when one considers that liquid modes and modal frequencies are affected by the amount of liquid in a tank. The inertia ratio's importance is apparent when one considers that the nutation frequency is a function of the effective inertia ratio. If the nutation frequency is at or near a liquid modal frequency then resonance can occur. Resonance involves rapid energy dissipation and consequently rapid nutation change. Nutation frequency (λ) is related to effective inertia ratio by the following equation:

$$\lambda = \omega \left|\sigma_{eff} - 1\right| \tag{4}$$

As Equation 4 shows, nutation frequency is proportional to vehicle spin rate. This is important because in most cases liquid modal frequencies on a spinning vehicle are also proportional to spin rate. This means it's usually impossible to escape from a resonance by changing spin rate. According to Equation 3, a resonance can be made less severe (i.e., the time constant can be made longer) by reducing the spin rate. However, this is not the same thing as escaping from a resonance.

There are two noteworthy exceptions to the observation that liquid modal frequencies are usually proportional to the vehicle's spin rate. The first exception is for partially-filled tanks at very low spin rates. If the spin rate is low enough for surface tension to have significant influence then the liquid distribution within a partially filled tank will be different from the distribution at higher spin rates. This affects the liquid flow pattern, mode shapes, and resonant frequencies. The second exception is for tanks that constrain the liquid within diaphragms or bladders. A diaphragm or bladder's equilibrium shape is governed, in part, by the magnitude of the centrifugal force. In other words, the shape is a function of spin rate. At high rates the equilibrium shape may be essentially independent of spin rate. However, for a range of low and intermediate spin rates the diaphragm or bladder shape and the liquid modes may have nonlinear dependencies on spin rate.

Non-Exponential Nutation Change

During subscale drop tests it's not unusual for the release transient to excite one or more liquid modes with frequencies that differ from the nutation frequency. The resulting attitude motion yields non-exponential nutation sensor outputs such as that in Figure 4, which has a clearly visible beating between an exponentially growing nutation and an exponentially decaying liquid mode. Behavior of this type is most likely to occur when a liquid modal frequency is near but not identical to the nutation frequency. Although this type of behavior can occur in flight on spinning vehicles that are subject to large transients, such as engine burns and separation events, the phenomenon is usually more subtle in flight than that shown in Figure 4.

To determine a dimensionless nutation time constant using data of the type shown in Figure 4 it is necessary to mathematically separate nutation from other components of the signal. The extracted non-nutation frequencies are the result of liquid motion, and these frequencies can be used to identify resonant conditions without those specific conditions being tested or flown. Resonance exists when the nutation frequency matches a liquid modal frequency. Hence, to find a resonance one can simply use Equation 4 to determine the effective inertia ratio that yields a nutation frequency equal to the extracted liquid modal frequency. In doing this it is important to remember that liquid modal frequencies are usually proportional to the vehicle's spin rate. Hence, resonant conditions are identified by solving Equation 4 for effective inertia ratio; not for spin rate. Although it is possible to identify conditions that cause resonance by mathematically separating a signal's components, this approach cannot be used

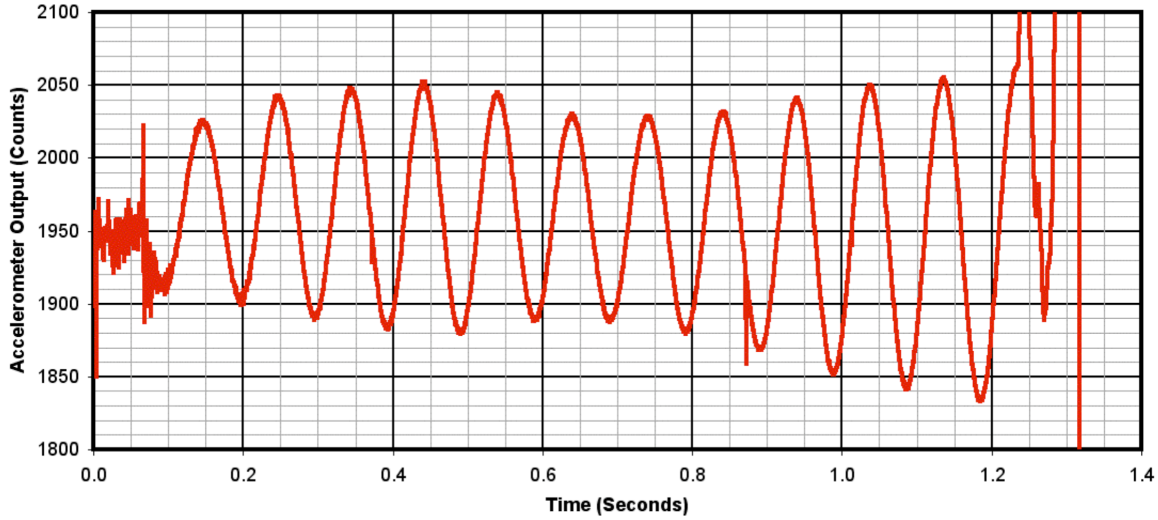

Figure 4. Drop test data showing beating between nutation and a liquid mode

to determine the divergent nutation time constant at resonance. The time constant can only be determined by direct testing or from flight data at the resonance. Despite that limitation, knowledge that a resonance exists is valuable because it lets vehicle designers know what conditions to avoid or, if resonance is unavoidable, gives designers a heads-up that further testing is required and that a robust active nutation control system may be needed.

Nutation Synchronous Motion

As previously discussed, nutation synchronous motion can occur if the vehicle's spin axis passes through a partially filled tank. Once a nutation synchronous mode is fully established the energy dissipation rate due to liquid motion is essentially independent of the nutation amplitude, provided the nutation angle is less than about 10 deg. In other words, kinetic energy loss is more like that from Coulomb friction than from viscous friction. If we let C_1 be the constant rate of change of energy and H be the vehicle's angular momentum then the nutation angle changes according to the following relationship

$$\theta = \sqrt{\frac{C_1 I_S t}{H^2\left(\sigma_{eff} - 1\right)} + C_2} \tag{5}$$

where C_2 is a constant of integration. Note that because kinetic energy is dissipated from the system, C_1 is negative. Figure 5 shows a nutation profile in which an initial exponential growth ($t < 0.3$ sec) transitions into nutation synchronous motion ($t > 0.4$ sec). In this example the transition to nutation synchronous motion occurred at a nutation angle of approximately 2 degrees. Note that nutation grows more slowly once the mode transition is complete. Because nutation does not change exponentially during nutation-synchronous motion, it is not valid to normalize the behavior using a dimensionless time constant. An alternative normalization technique must be applied.

TANKS WITH CYLINDRICAL SECTIONS

Tanks with cylindrical midsections and hemispherical ends have seen regular use during the past decade. In all cases, the tank's long axis has been parallel to the vehicle's spin axis. Because a significant number of vehicles have been designed and flown with such tanks, there is a large base of subscale drop test data on which to draw general conclusions. It's clear from the data that some characteristics of the behavior are relatively independent of the tank's location in the vehicle, while other characteristics depend on whether the tank's center is on the vehicle's spin axis or offset from the spin axis.

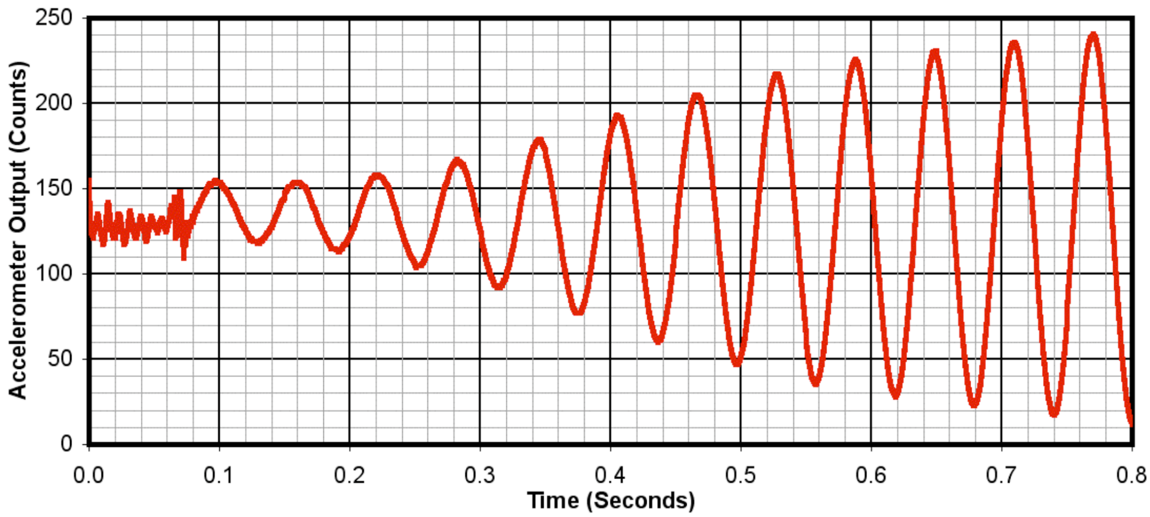

Figure 5. Drop test data showing transition to nutation synchronous motion

Centerline Tanks

Examination of data from a large number of subscale drop tests has shown that tanks with cylindrical midsections, hemispherical ends, and the long axis on the vehicle's spin axis are subject to two potentially troublesome liquid modes. The first is a subsurface vortex mode that can exist even when the tank is 100% full. The second is apparently a surface wave mode. The subsurface vortex mode typically has a natural frequency between 0.6 and 0.8 times the spin rate, with the exact value being a function of fill fraction and tank aspect ratio. This mode can potentially resonate with nutation on vehicles that have effective inertia ratios between 0.2 and 0.4. The nature of this mode is such that its effect can be mitigated with an annular baffle of a type first described by Pocha [13] and shown in Figure 6. Available data suggests that for best performance the baffle should be wide enough to penetrate near or into the ullage volume. Although annular baffles can increase the nutation time constant by an order of magnitude or more at inertia ratios near the resonance, the improvement usually comes at the cost of degraded performance at inertia ratios that are well away from the resonance.

The surface-wave mode appears to have a natural frequency between 0.3 and 0.5 times the spin rate, with the exact value being a function of fill fraction and other parameters. This mode can potentially resonate with nutation on vehicles with effective inertia ratios between 0.5 and 0.7 although the range can be greater if the tank center has a large offset from the vehicle center of mass. Evidence suggests that the mode involves nutation synchronous flow around the spin axis as shown in Figure 2. This means that the motion cannot be blocked by the annular baffles that are so effective on the vortex mode. Whereas annular baffles suppress the vortex mode by acting as dams that block the associated fluid flow, these same baffles appear to act on the surface wave mode mainly by increasing drag.

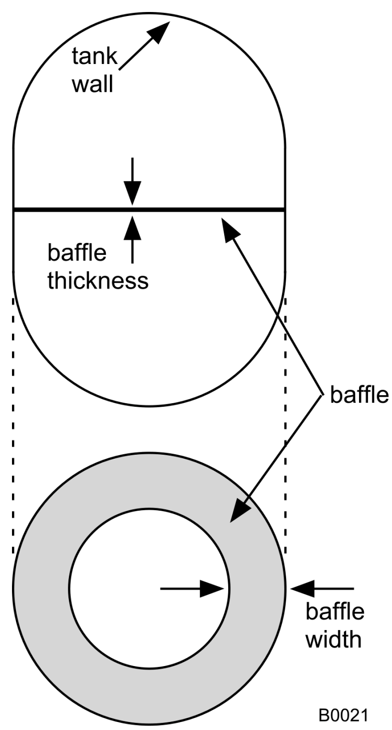

Figure 6. Annular baffle

A key influence of baffle drag on the surface wave is that it decreases modal frequency. Frequency decrease with increased drag is a normal characteristic of damped harmonic motion, and it is this behavior that may provide the principal benefit for vehicles with inertia ratios that are near but below the value that can cause resonance with the surface wave. Decreasing the modal frequency causes the resonance to occur at a higher inertia ratio. Tests indicate that adding washer-shaped baffles (and thereby increasing drag) shifts the resonance away from the nutation frequency, provided the nutation frequency is initially above the liquid modal frequency. The wider the baffle, the greater the drag, and the greater the frequency shift. Test data suggests that frequency shifts of 30% or more are possible and, depending on fill fraction and vehicle configuration, this may be sufficient to resolve a nutation time constant problem. It's clear, however, that for vehicles with inertia ratios between 0.5 and 0.7, an alternate baffle design may be more appropriate, although the nature of that design has yet to be determined.

It's noteworthy that the surface wave mode seen in centerline tanks with cylindrical midsections and hemispherical ends is has also been observed in spherical tanks, which can be considered as having cylindrical sections of zero length.

Off-Axis Tanks

Available subscale drop test data indicates that off-axis tanks with cylindrical midsections and hemispherical ends are susceptible to the same vortex mode as centerline tanks and that resonance can occur at effective inertia ratios in the range 0.2 to 0.4, with the actual resonance condition again depending on fill fraction, tank aspect ratio, and other parameters. Tests also show that, as in centerline tanks, annular baffles of the type depicted in Figure 6 can improve nutation performance at resonance by an order of magnitude, although this improvement comes at the expense of poorer performance at inertia ratios away from resonance.

As one might expect, centerline tanks differ from on-axis tanks in that tests to date have shown no sign of resonance at inertia ratios above 0.5. This is consistent with the belief that in centerline tanks the mode in question is the result of nutation synchronous flow. Because nutation synchronous motion requires circulation around the spin axis, it cannot be supported in a tank that is offset from the spin axis. On the other hand, there is test data suggesting that highly elongated off-axis tanks (length/diameter >2.5) are susceptible to waves that run parallel to the vehicle's spin axis (parallel to the tank's long axis) and that these waves can have low enough frequencies to resonate with nutation. Tests have shown that surface waves of this type can cause significant nutation problems at fill fractions as high as 0.98. Unfortunately, there is insufficient test data to map out the range of conditions for which this type of behavior can occur, to fully assess its severity, or to determine the type of baffle that can most effectively suppress it.

TANKS WITH DIAPHRAGMS OR BLADDERS

Diaphragms and bladders are elastic barriers that separate liquid propellants from the pressurant gas. A diaphragm is essentially a flexible wall. In a diaphragm tank the contained liquid is in direct contact with both the flexible barrier and the portion of the tank's "rigid" wall that is on the propellant side of the diaphragm. In a bladder tank the propellant is entirely within a flexible inner container and the tank's rigid walls are not wetted. In both diaphragm and bladder tanks the flexible barrier causes the liquid to be within an asymmetric compartment unless the elastic barrier is fully distended. This asymmetry is a consequence of the elastic barrier being able to bend much more easily than it stretches, which causes the barrier's surface area to be essentially independent of the amount of liquid in the tank. The effect of nearly constant surface area on shape can be seen in the photographs in Figure 7.

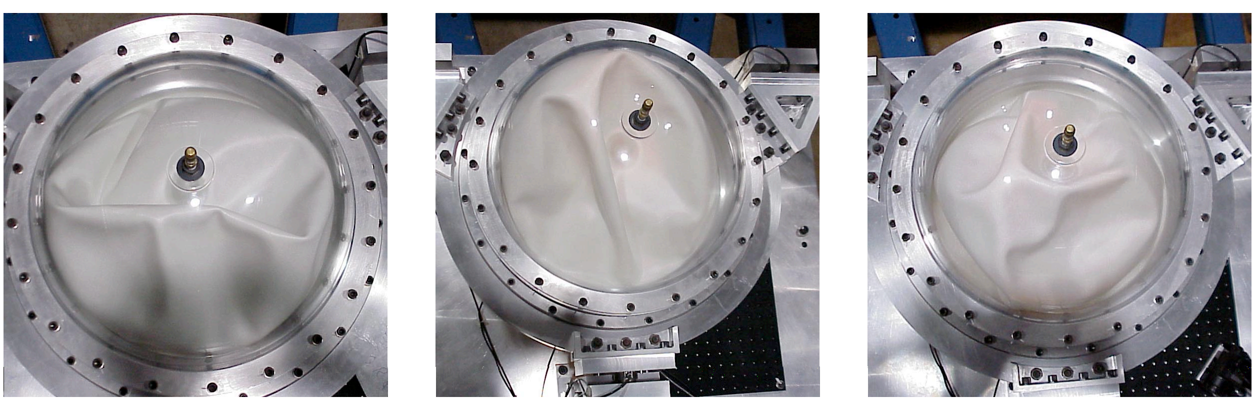

Figure 7. Examples of diaphragm equilibrium shapes in a 71% full tank (photographs courtesy Southwest Research Institute)

Having liquid within an asymmetric container has several consequences for energy dissipation and the resulting nutation change. The most obvious effect is that surface wave mode shapes and modal frequencies will be more sensitive to fill fraction than in a tank without a diaphragm or bladder. Furthermore, if a surface wave is excited, hysteresis associated with cyclic bending will significantly increase modal damping. Depending on circumstances, this increased damping could so suppress the surface wave that nutation change is slowed, or it could dramatically increase the energy dissipation at resonance. The latter effect is more likely to occur if the tank is far from the vehicle's center of mass and thus subject to greater cyclic acceleration. Asymmetry also raises the possibility that subsurface inertial waves may be excited. This must always be considered when liquid is contained within a non-spherical compartment. As with surface modes, subsurface inertial wave frequencies and mode shapes may depend strongly on the diaphragm or bladder shape, and thus on the fill fraction. Finally, energy dissipation from bulk fluid motion is affected by the liquid's "free" surface being in contact with an elastic solid instead of a gas because viscous drag is increased as the fluid moves past the wrinkled surface.

Using test and flight data to predict the performance of other vehicles with "identical" diaphragms or bladders is complicated by uncertainties associated with non-repeatability in wall thickness and variations in equilibrium shape. Due to variability in the molding process, diaphragm and bladder thickness can vary from sample to sample and from different locations on the same diaphragm or bladder. This variability holds for both subscale test tanks and full scale flight tanks. Furthermore, the number and shape of dimples and wrinkles in a diaphragm or bladder may depend on the sequence of events that preceded the spinning operation of interest, with uncertainty in the shape being greatest for an on-axis tank. Variations in these and other parameters may shift a liquid resonance so that it occurs at a somewhat different fill fraction or inertia ratio than previous tests or flight data might indicate. Because of this, extra conservatism must be used when applying the results of diaphragm tank tests or when extrapolating flight performance to other configurations.

A recent series of subscale drop tests explored the impact of diaphragm equilibrium shape on nutation time constant and the results were dramatic. Depending on the how the diaphragm was wrinkled, the dimensionless time constant was observed to vary by more than an order of magnitude for the same combination of fill fraction and inertia ratio. In these tests the tank was mounted on the spin axis with the diaphragm's attachment plane perpendicular to the spin axis when the spacecraft is mounted on a upper stage. During initial tests of this configuration, inconsistencies in results for similar combinations of inertia ratio and fill fraction led to the observation that the diaphragm had more than one possible equilibrium shape and that a shift from one equilibrium shape to another could change the dimensionless time constant by an order of magnitude. It was found that by prodding the diaphragm it was possible to produce all of the equilibrium shapes approximated in Figure 8 when the fill fraction was 0.7. It's unlikely that these four shapes represent the only possibilities.

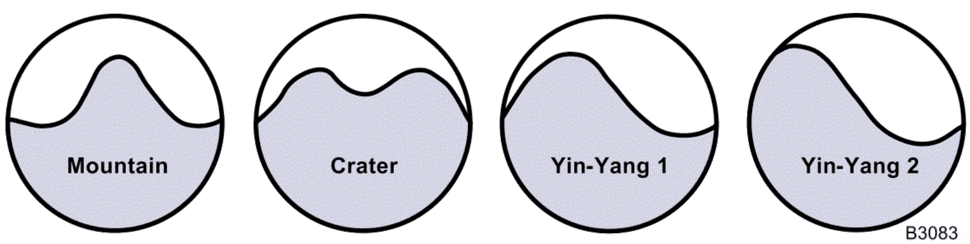

Figure 8. Possible diaphragm equilibrium shapes

SUMMARY OF OBSERVED PROPELLANT TANK INFLUENCES

The following is a summary of observed behavior of propellant tanks that have flown on spinning space vehicles or that have been subject to spinning ground test.

Non-Diaphragm Tanks

Spherical tanks have extensive flight and test history. Severe nutation synchronous resonance has been observed in partially-filled tanks that are mounted on the spin axis. Energy dissipation in off-axis tanks and in non-resonant on-axis tanks is dominated by flow past internal hardware. In non-resonant conditions, the energy dissipation rate tends to increase with fill fraction, with the maximum dissipation often occurring at 100% fill.

Spheroidal tanks have only a limited test history. However, tests show that even small deviations from spherical can greatly increase energy dissipation.

Sphere-cone or "conisphere" tanks have extensive flight and test history and have been shown to be subject to severe inertial wave resonances at many combinations of fill fraction and inertia ratio. This is probably the most extensively tested tank configuration, but the data is largely proprietary and was unavailable for this study. Although this tank shape saw frequent use two decades ago, the author has found no indication that propulsion system designers plan to use it in future designs.

Cylindrical tanks have been extensively studied, although the focus has been largely on spinning artillery shells in which the tank's symmetry axis is coincident with the spin axis. In this context, severe resonances have been identified in partially filled and completely filled tanks. This author is aware of only one use of a nearly cylindrical tank on a space vehicle, and that configuration had the tank's symmetry axis perpendicular to the spin axis. Test and flight performance of a 100% full tank showed that particular configuration to be relatively benign.

Cylindrical tanks with hemispherical ends have seen regular use during the last decade and have thus been subject to a variety of test programs. Experience is limited to tanks with the symmetry axis parallel to the vehicle's spin axis. Resonance has been observed in both on-axis and off-axis tanks; including completely-filled tanks. A vortex-mode resonance that exists at inertia ratios between 0.2 and 0.4 can be suppressed with annular baffles. These baffles are less effective in dealing with a nutation synchronous surface wave resonance that occurs in partially-filled centerline tanks at inertia ratios between 0.5 and 0.7. An alternative baffle design could probably suppress nutation synchronous motion but such a baffle has yet to be developed or tested. Finally, highly elongated off-axis tanks appear to be subject to a surface wave that runs parallel to the tank's long axis. This wave can exist at fill fractions as high as 0.98. There is insufficient test data to determine the combinations of inertia ratio, fill fraction, and tank aspect ratio for which longitudinal slosh waves can resonate with nutation.

Hemispherical tank tests on an air bearing have shown strong resonances for a fill fraction of 1.0. Although this tank shape is unlikely to see application on a space vehicle, the test results reinforce the conclusion that non-spherical tanks are susceptible to vigorous subsurface flow.

In considering the above performance summaries it is essential to recognize that tank shape is only one of many characteristics that must be considered when evaluating the influence of contained liquids on nutation performance. In particular, the configuration of internal hardware (baffles, sumps, drain tubes, surface tension vanes, etc.) can have a profound effect on vehicle behavior.

Tanks with Diaphragms or Bladders

Spherical diaphragm tanks have a limited test history. Although some resonances have been seen in ground tests, there is insufficient test and flight history to know the true resonance risk.

Cylindrical tanks with hemispherical ends have been tested for several spacecraft programs. These tests showed strong sensitivity to diaphragm equilibrium shape, although the characteristics and full magnitude of the sensitivity has been only partially mapped out. Resonance has also been seen in a bladder tank of this shape.

General Observations

Care must be taken when applying existing flight or test data to new configurations. This is especially true for non-diaphragm tanks because it seems that nearly every spinning vehicle uses a tank with a different propellant management device, even if it's designed by the same organization for a tank with dimensions nearly identical to one that flew before. Tests have shown that nutation performance can be very sensitive to PMD shape, dimensions, and flexibility. Available data indicates that internal hardware increases the dimensionless time constant for operations near a liquid/nutation resonance and decreases the DTC for operations away from resonance. In other words, for a minor axis spinner internal hardware tends to improve performance at or near resonance but tends to degrade performance away from resonance. Test data also indicates that PMD flexibility can reduce its influence on nutation performance.

A spinning vehicle with onboard liquid does not have the same dynamic characteristics as a simple rigid body. Instead, it's a dynamical system with potentially strong coupling between the liquid flow and the vehicle's 3-axis rotational motion. One effect of this coupling is that "nutation" is actually a system mode with a frequency that differs from what one would expect if the liquid was frozen in place. In other words, there is a difference between the vehicle's *effective* inertia ratio (liquid frozen in place) and its *apparent* inertia ratio (liquid mobile). Subscale drop tests have shown that this difference can be 15% or more if the liquid represents a large fraction of the vehicle's mass or moment of inertia. Furthermore, the shift in nutation frequency tends to be toward resonance. This means that the system may be closer to resonance than one might expect from mass properties that assume the liquid to be frozen in place.

The table below lists the minimum dimensionless time constants recorded during this study for a variety of tank configurations. Because there are large knowledge gaps in the parameter space it's unlikely that these values represent absolute worst-case. However, they are tabulated here because they provide a sense of which configurations have the greatest potential for causing nutation performance problems. In this list the most benign configuration is an off-axis sphere with no internal hardware. At the other extreme is an elongated cylindrical tank with hemispherical ends. This last configuration has been observed to have DTC's that are two orders of magnitude shorter than the worst values recorded for simple spherical tanks. All tabulated values are for tanks without baffles.

Minimum Dimensionless Time Constants Identified During the Study

Tank Shape	Location	Internal Hardware	Minimum DTC
Sphere	Off-axis	None	7.12
Sphere	Off-axis	PMD	3.62
Cylinder with hemispherical ends	Centerline	Diaphragm	1.92
Transverse cylinder	Centerline	None	1.59
Sphere	Centerline	Diaphragm	1.42
Sphere	Centerline	None	0.51
Cylinder with hemispherical ends	Centerline	PMD	0.20
Cylinder with hemispherical ends	Off-axis	PMD	0.07

Although a baffle of proper design can suppress a troublesome liquid mode, it's important to recognize that baffles are not a panacea. They may have no effect on other modes with different flow patterns and could possibly introduce new detrimental modes. Experience has shown that although suppressing a resonance can increase the nutation time constant for one combination of fill fraction and inertia ratio, the increased drag usually degrades performance in other portions of the parameter space. Thus, baffles should only be used for parameter combinations where their performance has been validated by test.

THE ANALYTICAL CHALLENGE

Each of the existing methods for modeling the motion of liquid propellant on a spinning vehicle has significant limitations. The obvious high-fidelity approach is to use a fluid dynamics software package. This method, however, has several major shortcomings. First, it is complex and time consuming. Second, it has been reported that some fluid flow packages don't model Coriolis effects properly, which limits the accuracy in modeling inertial waves on a spinning vehicle. Third, if the propellant management device is flexible, it's bending can have a significant influence on the liquid behavior and must be modeled. Most packages cannot easily model the coupled interaction between fluid flow and the flexing of surface tension vanes, diaphragms, or bladders. Fourth, fluid flow packages don't model the effect that the liquid has on the vehicle's 6 degree-of-freedom motion. In other words, most "high-fidelity" analytical models mathematically decouple what is in reality a highly coupled system. Finally, fluid flow models tend to be least accurate in their modeling of turbulent drag effects, and it is the energy dissipation associated with drag that is usually of greatest concern. From these observations it's unclear whether any existing software package can accurately quantify the effect of liquid motion on a spinning vehicle's nutational dynamics.

Mechanical analogs are a commonly used alternative to detailed fluid modeling. A significant advantage of this approach is that it can easily be incorporated into a simulation or other software package with full coupling between the "liquid" motion and the vehicle's rotational dynamics. The main disadvantage is that a simple analog cannot emulate all aspects of the propellant motion. Often the best that can be done is to select a model that emulates the dominant behavior. Of course this leads to the question of what is the dominant behavior. Is it free-surface sloshing, bulk fluid motion, or a subsurface vortex mode? This question is difficult to answer without testing. An even more difficult issue is how one selects values for key parameters. Choosing correct values for the analog's natural frequency and damping rate is a particularly thorny problem if test and flight data are unavailable.

Small-amplitude free-surface sloshing is often represented by a simple pendulum with a massless rod and a bob that is a point mass. For an off-axis tank the pendulum's natural frequency is typically well above the nutation frequency.* On the other hand, bulk fluid motion in a partially filled off-axis tank may be best modeled as a short pendulum with a substantial self-inertia. This pendulum's natural frequency is very low — well below nutation frequency. Because free-surface sloshing typically has a "high" frequency and bulk motion has a "low" frequency, a single simple pendulum model cannot adequately emulate both behaviors. The pendulum modeling problem is even more complex if the spin axis passes through the tank. In a centerline tank the surface wave behavior of greatest concern is often the nutation synchronous mode, in which the liquid swirls around the tank in a single direction at nutation frequency. In this type of motion the modal mass is a function of nutation amplitude. This is difficult to model with a simple pendulum. Finally, for both on-axis and off-axis tanks, the most severe limitation of pendulum models is that they cannot emulate subsurface inertial waves.

In the extreme, a full or nearly full tank may best be modeled using one or more wheels coupled to the vehicle body by viscous friction and possibly tortional springs. In this situation there is no free surface and thus no slosh mode. Nevertheless, test and flight experience has shown that substantial energy dissipation is possible in a completely full tank. Whether bulk fluid motion is modeled as a pendulum, a wheel, or another analog, the damping rate depends almost entirely on the internal hardware configuration. Once again, there are no good purely analytical methods for determining the PMD-induced damping rate without test or flight data.

Perhaps the biggest challenge is to adequately model the behavior of liquids in tanks with diaphragms or bladders. As discussed previously, the nutation characteristics can be significantly affected by a diaphragm's equilibrium shape. If the diaphragm is not fully distended it typically has more than one possible equilibrium shape, especially if the tank is located on the vehicle's spin axis.

To the author's knowledge, reliable mechanical analogs have yet to be developed that emulate the complexity of vortex modes. One possibility is to use multiple wheels that are coupled to the vehicle's rotational motion with springs and viscous dampers. However, once again there is the difficulty of how one selects the appropriate parameters for such an analog. Complicating the problem is the fact that some configurations have multiple modes, each with a different frequency.

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* Highly elongated off-axis tanks are an exception. Such tanks can support slosh waves with frequencies that are below the spin rate and that can thus resonate with nutation. A mass-spring-damper model might be more appropriate for surface waves in tanks of this type.

Experience has shown that with sufficient work it's possible to construct a model that accurately emulates observed test or flight performance. The difficulty, however, is in developing a model that can accurately *predict* performance. Equivalent mechanical models can be used in simulations that adequately emulate the nutation behavior of a vehicle with onboard liquids *only if the model and its parameters are based on test or flight data.* Experience has shown that the behavior of a nutating vehicle with onboard liquids cannot be predicted using a purely analytical model that has no flight or test data behind it.

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